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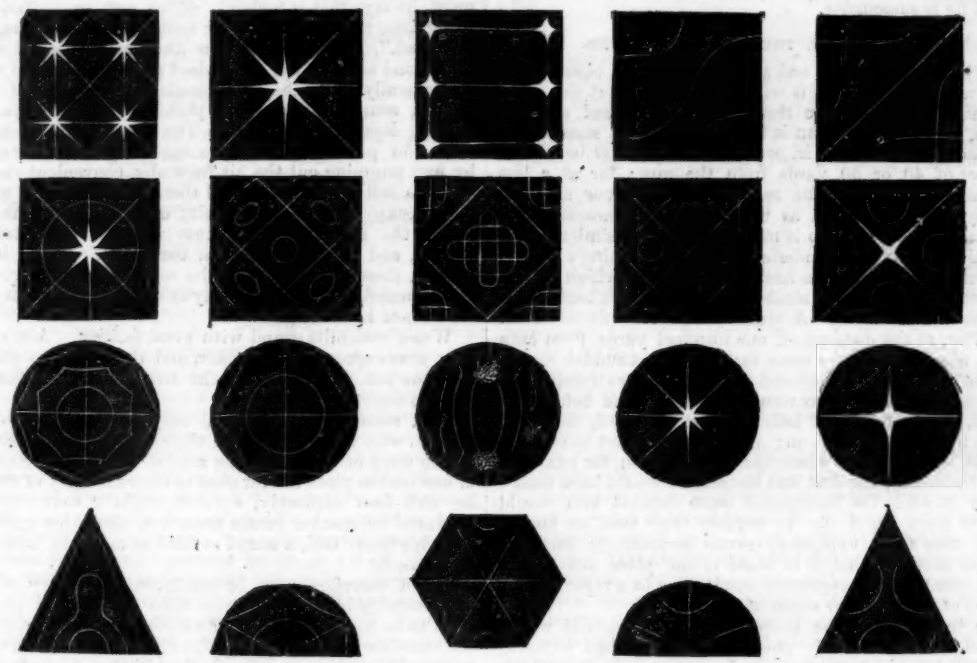
THE PHILOSOPHY OF THE EXTERNAL SENSES. II.



EXAMPLES OF FIGURES PRODUCED BY VIBRATING SURFACES.

ON THE NATURE AND SOURCES OF SOUND.

Nature inanimate employs sweet sounds,
But animated Nature sweeter still,
To soothe and satisfy the human ear.—COWPER.

INTRODUCTION.

"IF the atmosphere be considered as a vast machine, it is difficult to form any just conception of the profound skill and comprehensiveness of design which it displays. It diffuses and tempers the heat of different climates; for this purpose it performs a circulation, occupying the whole range from the pole to the equator, and while it is doing this, it executes many smaller circuits between the sea and the land. At the same time, it is the means of forming clouds and rain, and for this purpose, a perpetual circulation of the watery part of the atmosphere goes on between its lower and upper regions. Besides this complication of circuits, it exercises a more irregular agency, in the occasional winds which blow from all quarters, tending perpetually to restore the equilibrium of heat and moisture. But this incessant and multiplied activity discharges only a part of the functions of the air. It is, moreover, the most important and universal material of the growth and sustenance of plants and animals, and is for this purpose everywhere present and almost uniform in its quantity. With all its local motion, it has also the office of a medium of communication between intelligent creatures, which office it performs by another set of motions, entirely different both from the circulation and the occasional movements already mentioned; these different kinds of motions not interfering materially with each other; and this last purpose, so remote from the others in its nature, it answers in a manner so perfect and so easy, that we cannot imagine that the object could have been more completely attained, if this had been the sole purpose for which the atmosphere had been created. With all these qualities, this extraordinary part of our terrestrial system is scarcely ever in the way: and when we have occasion to do so, we put forth our hand and push it aside without being aware of its being near us."—WHEWELL, *Bridgewater Treatise.*

The above eloquent passage forcibly reminds us that a large amount of knowledge is necessary to a due appreciation of the many blessings we enjoy from the constitution of the physical world, maintained as it is so constantly by an Almighty hand. Health, and strength, and reason, are indeed precious gifts vouchsafed to the majority of mankind, and these are sufficient to impress us with gratitude: but when by a careful examination of our earthly dwelling-place, we see the thousands of wise and beautiful adaptations whereby the world has been prepared for living creatures, or they for the world, we feel how natural was the exclamation of the inspired Psalmist, "Lord, what is man that thou regardest him, or the son of man that thou visitest him."

If we attend but to one of those minor offices of the air—the production and propagation of certain pulses which, falling upon the ear, produce sound,—abundant material may be offered for instruction and admiration. How many delightful associations do we connect with sound! how many of the beauties and the sublimities of nature! how much of the business and the pleasures of social life! The murmuring of waters, the whispering of winds, the sweeping of the blast through the forest, the rush of the cataract, the roaring of ocean and the voice of the thunder,—these are a few of the distinctive characters of different objects which the atmosphere presents to us in so perfect a manner that we can distinguish any one of them amid a multiplicity of minor sounds. And then, how beautiful is that combination which makes up many a rural concert! the woodman's axe, the lowing of cattle, the cawing of rooks, the hum of insects, the distant village bells, the evening song of the thrush, the bleating of sheep, sounds apparently unconnected, and some of them inharmonious, yet, taken with their poetical

associations, can scarcely be heard without emotion. But "the articulate character of sounds is for us one of the most important arrangements which exist in the world; for it is by this, that sounds become the interpreters of thought, will, and feeling, the means by which a person can convey his wants, his instructions, his promises, his kindness, to others: by which one man can regulate the actions and influence the convictions and judgments of another. It is in virtue of the possibility of shaping air into words, that the imperceptible vibrations which a man produces in the atmosphere become some of his most important actions, the foundations of the highest moral and social relations, and the condition and instrument of all the advancement and improvement of which he is susceptible."

Section I. On the Nature of Sound.

If we listen to a sound, and at the same time observe the cause which produces it, it will be remarked that the cause has ceased to act before the sound has reached our ear. When, for example, a gun is fired, the flash is seen before the report is heard, that is, provided the observer be at the distance of 40 or 50 yards from the gun; for at a less distance the flash and the report seem to occur simultaneously. In proportion as the distance is increased, the interval between the two is more marked. A similar result is obtained during a thunder-storm: the lightning's flash is seen before the thunder is heard, and the time which elapses between the two gives a measure of the distance between us and the thunder cloud. A number of persons placed on the same line, at the distance of one hundred yards from each other, would not at the same instant hear a sudden sound, such as an explosion, produced at one of the extremities of this line: the first person would hear the sound before the second, the second would hear it before the third, the third before the fourth, and so on; and it is important to remark, that at the moment when the third person, for example, heard the sound, the first and the second would have ceased to hear it, while the fourth and those beyond him would not yet have heard it. It appears then that an abrupt sound, such as an explosion, travels successively from one place to another; that it is heard in one place only at the same instant, and consequently that it must be a rapid motion capable of affecting our organ of hearing.

The invention of the air-pump enabled natural philosophers to explain many phenomena which had hitherto been involved in some degree of mystery; among which was the following:—In the year 1705 Hauksbee contrived an apparatus by means of which a bell might be rung in the receiver of an air-pump. On removing a portion of the air from the receiver, the sound of the bell was perceptibly diminished, and became feeble in proportion as the air was removed. A curious objection occurred to him respecting the results of this experiment:—"Whether the sonorous body in such a medium might not so suffer, or undergo such a change in its parts, as to be rendered incapable of being put into such a motion as is requisite for the action or production of sound?" He therefore instituted another experiment. A strong receiver, inclosing a large bell, was firmly screwed to the table of the air-pump: this was inclosed within another receiver, and the air between the two removed. On causing the inclosed bell to vibrate, no sound was heard, although the bell itself was surrounded by air; the existence of a vacuum between the two receivers as completely prevented the transmission of sound as if the bell itself were in vacuo. It will be seen therefore that sound cannot be propagated from empty space; for although the sound-producing body, under such circumstances, is thrown into a vibratory state, yet there is no path to convey these vibrations to the ear, and consequently there is no sound.

Sounds excited in the atmosphere diminish in intensity as they are elevated, not only because the distance from which we hear them is increased, but also because the air becomes more and more thin, or rarefied, in ascending from the surface of the earth, and at the height of about forty-five miles, at which the atmosphere most probably ceases to exist, and where is placed the boundary line between the air and the wide fields of space, sound also must cease. Thus the most violent terrestrial noises cannot escape the limits of the atmosphere: they become weaker and weaker as they ascend, and are soon altogether extinguished. So also no sound can reach this earth from the regions of space. The light of many a meteor may strike the eye, and we may in some measure be aware of terrific volcanic eruptions in the moon, but they are incapable of affecting our planet, because between us and them the Almighty has indeed fixed a great gulf, over which it is impossible to pass.

We need not ascend far from the earth's surface to become painfully aware of the thinness of the air, and the diminished intensity of sounds. On the summit of Mont Blanc a pistol produces less noise than would a small cracker in the valley below, and at great heights in balloons the sound of the voice of the aeronauts is scarcely appreciable.

The experiments which our countryman, Hauksbee, had the honour first to perform, are very valuable, and still retain their place in the science of sound; but they led him to an incautious conclusion. Speaking of his last experiment, he says that it "plainly shows, and seems positively to confirm, that air is the only medium for the propagation of sound." Now it was soon discovered that all elastic fluids, and even solids, and indeed all substances to which we generally apply the term elastic, were capable of transmitting sounds, more or less perfectly according to their varying degrees of elasticity. The air-pump furnishes the means for producing sound in various gases and vapours, by first pumping out the air from any convenient vessel in which a bell is suspended, and then allowing a gas to flow in to occupy the place of the air; or a liquid, such as ether, which the moment it falls into vacuo is converted into vapour, and fills the whole of the vessel. If the bell be rung in these various media the sound is always produced, accompanied, however, by many curious modifications which we cannot here consider.

Water transmits sound with great facility. A diver can hear words spoken above water, and those above water can hear the sound produced by the diver when he strikes two pebbles together.

That solids transmit sound may be familiar to most persons who have performed the curious experiment with a long piece of wood, such as a felled tree by the road side. If one person place his ear close to one extremity of the tree, he will hear distinctly, even so slight a sound as that produced by another person scratching the other extremity with his finger nail, a sound so faint as not to be heard even by himself.

Sound therefore may be considered as a very complex phenomenon, in which no less than six distinct processes seem to be necessary. 1st, the excitement of a motion in the sounding body; 2nd, the communication of this motion to the air, or other substance placed between the sounding body and our ears; 3rd, the propagation of such motion from particle to particle of the air, or other intermediate body, in due succession; 4th, its communication from the particles of the air, or other intermediate body, adjacent to the ear, to the ear itself; 5th, its conveyance in the ear, by a certain mechanism which we have already described, to the auditory nerves; 6th, the excitement of sensation. Sound therefore must be considered as a *sensation* within us, and nothing but a series of *motions* exterior to us. The ear is therefore as necessary to sound as are the vibrations of matter. Without the ear there is probably no such thing as sound in nature—the mighty Niagara has no voice of thunder when no ear is present to participate in the disturbance it excites—the ocean lashing the shingles on the beach—the artillery of the sky, and the fearful blast of the tempest, these have all their peculiar expressions for us, because we participate in the stupendous motions they produce in the air, and in surrounding matter; but in the absence of the animal ear, they consist of motions merely, not sounds. They are the beginnings of perceptions, but not the perceptions themselves, in the same way we may consider perception to be necessary to sensation, but altogether distinct from it.

The most accurate experiments which have yet been made render it probable, that when a body performs about sixteen vibrations in a second the lowest musical note is produced which can in general be appreciated. We must distinguish between *musical* sounds and *noises*, because our means of ascertaining what rapidity of vibration produces a noise or mere sound are uncertain. Musical tones can be compared with some fixed standard, and the number of vibrations within a given time calculated with ease and certainty; whereas a noise is due to impulses so irregular that it cannot be brought in unison with a musical note, and therefore its value cannot be calculated.

Every continued sound is composed of frequently recurring vibrations, from sixteen up to many thousand, during a second of time. The effect on the ear, for any given

number of vibrations between these limits, is that of one sustained sound, and the ear is incapable of resolving it into the separate vibrations which compose it. In the same way, if a yellow and a blue powder be intimately mixed, the eye loses the impression of the component colours, and acquires a new impression—that of green. So also if we pass the finger over the surface of a finely-cut file, we cannot appreciate the grooves individually, but only a general roughness of surface.

Section II. On the Sources of Sound.

It will be instructive to inquire somewhat in detail into the sources of sound, with a view to ascertain the modes of vibration of various elastic substances. Those best adapted to our purpose are, 1. Strings. 2. Plane surfaces. 3. Curved surfaces. 4. A confined column of air; and 5. The human voice.

1. *The Vibration of Strings.*

Fig. 1.

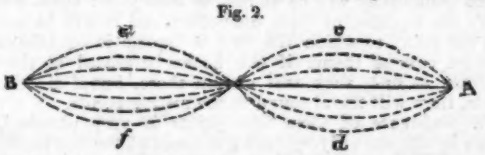
In fig. 1 a string A B is stretched tightly between two fixed points. If we draw the string aside into the position of A c B, a certain resistance will be experienced, which increases with the displacement. Now it is obvious that the path A c B is longer than the right line A, B, and the string, in order to occupy the former position, must have its fibres or particles separated, or strained somewhat farther apart. The resistance to this separation constitutes what we term the elasticity of the string—a property common to all substances, but in various degrees. The moment the string is liberated it darts back to its former position; but, as a momentum or force of motion is acquired by every moving body, so the string is not only carried back to A B, but passes beyond this position as far as A *d* B. This can only be brought about by a straining, or separation of particles similar to that which before occurred, and again the force of elasticity urges the string to return to its rectilineal position: this again creates a momentum which carries it a second time nearly to A c B, and these repetitions continue until the string finally attains rest. This it would never do, were it not that the excursions on either side of the normal position gradually decrease in extent on account of friction at the two extremities, and of the resistance of the air. These oscillations continue to diminish in extent as the string gradually attains the position A *e* B, and A *f* B, which, in its turn, decreases to A *g* B, and A *h* B, and finally the oscillations are reduced to nothing.

But it is a most important and beautiful law, that whether the excursions be large or small, they are performed in equal times, thus furnishing an analogy to the oscillation of the pendulum. The explanation is simply this:—the farther the string is removed from the position of rest, the greater is the elastic tension, and consequently the greater is the momentum and velocity with which it returns to its original position; and these two elements, the extent of the displacement, and the rapidity of the return, are found to increase in exactly the same ratio.

Every passage of the string over the position of rest is called a vibration; and the most convenient mode by which two or more velocities of vibration can be compared is by choosing some small unit of time, and reckoning the number of vibrations which occur in each. This unit has been fixed at one second, and the estimate of comparative velocities is conveniently made by means of it.

Now let us suppose that in the string the displacement, whether large or small, gives a velocity of vibration equal to 100 in a second: let the centre of the string be now fixed,

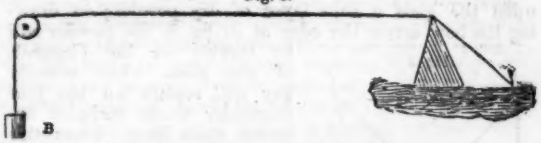
Fig. 2.



as in fig. 2, and the string drawn from its position at *c* or *e*: it will now be found that the number of vibrations in a second of time is exactly doubled.

But if, instead of varying the length of the string, we vary the tension or the force with which it is stretched, we find the following results: the rapidity of vibration increases as the square root of the tension: this it will be observed is a different ratio from the preceding, and is ascertained thus—suppose we had an arrangement by which one end of the string is fixed as in fig. 3, and the other, passing over a

Fig. 3.



pulley, is attached to a weight which gives it a certain degree of rigidity or tension: suppose that the weight attached is 5 pounds, and the resulting tension is such that the string vibrates 100 times in a second; to make the vibration twice as rapid, the weight must be increased the square of 2, or 4 times: to make the rapidity 3 times as great, the weight must be the square of 3, or 9 times as great, and so on. This same mode of experiment may be adopted for showing the fundamental fact that below a certain rapidity of vibration, no perception of sound is induced. If the weight attached to B be very small, and the string be struck at the middle of its length, the vibrations will be sufficiently slow for the eye to follow them, and if the number be less than 16 in a second, no sound will be heard; but if an additional weight be appended to B, so as to increase the tension of the string, the rapidity of vibration will be increased—the eye will not be able to count the vibrations, and sound will be audible: and in proportion as the weight is increased, so does the sound become more distinct and more elevated in pitch.

The third circumstance which modifies the rapidity of vibration is the thickness of the string: by doubling the thickness of a cylindrical string we obtain 4 times the bulk or mass, and it is found that if we have two strings of equal length and equal tension, to produce twice as great a velocity of vibration in one as in the other, requires that it should be twice as thick, or 4 times the sectional area. This relates to the comparison between the frequency of vibration in two cords of which the length, thickness, or tension are in a different ratio: but with regard to the absolute number of such vibrations in a second of time, recourse is had to a mode of calculation which is not sufficiently elementary to obtain a place here.

2. *The Vibration of Plane Surfaces.*

If a plane surface, such as a square piece of glass, be held in the centre by any mechanism which will leave the edge free to vibrate in a direction perpendicular to the plane of the glass, and a violin-bow be drawn across one of the edges, it will set the whole plate, with the exception of the part by which it is held, into vibratory action. The manner in which the vibration of one part of the glass induces similar vibrations in the other, will be better understood, if we first consider a piece of glass to be fixed at one edge, and vibration excited at the opposite edge.

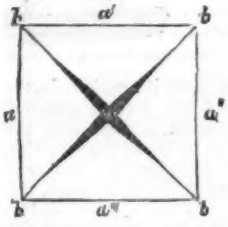
Let a slip of glass, (*a* fig. 4) be fixed firmly at one end into a block of wood. If the edge *a* be bent down to *c*, it will return with great rapidity to its former position *a*, when the disturbing force is removed: but in so doing it acquires a momentum which carries it to the other side of the plane of repose as far as *b*, nearly as far above its original position as the disturbing force had depressed it below the same: the reasoning which was applied to the case of a string, will likewise apply here: the second displacement will be followed by a second effort to reach the position of repose, and that will again be nullified by the impossibility of the motion of the glass being terminated at the precise point required: thus is engendered a series of vibrations alternately above and below the plane of repose, but the deviation from that plane becomes less and less at every vibration, on account of the friction at the end *a*, and of the resistance of the air, (the same two causes which retard and ultimately extinguish the oscillations of a pendulum).

Fig. 4.

The remarkable isochronism, or equal-timedness, in the vibrations is observable as well as in the stretched string: whether the original displacement from the position of

repose be great or small, the vibrations are performed in equal times, depending on the proportion existing between the length, breadth, and thickness of the glass. But if a square piece of glass be fixed at the centre and a fiddle-bow be drawn against the edge, the stationary position of the point causes a remarkable break in the continuity of the vibration from one edge to another: the nature of this obstruction is best shown by previously sifting upon the glass a thin layer of dry powder; on drawing the bow across the edge at *a*, fig. 5, the powder will be thrown on the diagonals of the glass, while scarcely any will remain on the four triangular spaces included between those lines. From this we learn that the diagonals of the plate are almost entirely stationary; that the points *a* *a'* *a''* *a'''* are in active vibration, which vibrations decrease in extent as we proceed from those points to the centre *a*, or to the corners *b*. It also follows that at the moment the section *a* is below the plane of repose, the opposite section *a''* is also below the same plane, but the other two portions *a'* *a'''* are *above* that plane.

Fig. 5



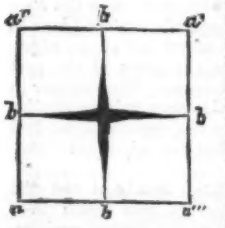
We will endeavour to show why this alternation of position is necessarily brought about: let fig. 6 represent a

Fig. 6.

horizontal section of the plate, of which the middle point *a*, is one of the diagonals or corner lines: if by the impulse of the bow, the part *a b* be depressed below its natural level, its under, or convex surface is necessarily greater in extent than the upper, or concave surface, as it forms a similar portion of a larger concentric curve. The particles of the under side of the glass, therefore, must be somewhat strained, or drawn farther asunder, to admit of that extension of surface: but such is the tendency to an equalization of pressure among all bodies, that in order to compensate for the expansion of the lower side of the glass, in the portion *a b*, the portion *a c* takes a curvature upwards, that is, it becomes convex on the upper, and concave on the lower surface, while the other portion *a b* is the reverse of this.

In fig. 5 the powder is collected on the diagonals of the plate; but if the bow be applied near one corner, the powder assumes a rectangular figure, as shown in fig. 7: a similar explanation will apply here: the corner of the plate to which the bow is applied, is drawn down from its original position, and induces a similar displacement in all the particles around it: this displacement, by making the under surface at and near the point *a* convex, while the upper surface becomes concave, causes an unequal expansion of the two surfaces, which continues to the points *b*; the maximum of vibration is at *a*, and it decreases towards *b*, where it attains its minimum, but at those points a tendency to an opposite curvature of the adjoining portion commences, for the reasons before stated; and the portions *b a''' b* and *b a' b* become convex upwards: these two again act on the fourth division (*b a b'''*) which becomes convex on the under, and concave on the upper surface, the same as the first portion.

Fig. 7.



These remarkable phenomena have been traced through a very extensive range of modifications. By holding the plate at the centre, and applying the bow to various parts of the edge; or by fixing the plate in the middle of one side, and applying the bow to different parts of the other three sides; or by holding the plate at one *corner*, and exciting vibration at different positions with regard to it, an almost endless variety of figures have been produced. A few examples are given at the head of this article. In these and similar examples the lines occupied by the accumulated trains of powder are called nodal lines: they represent the parts of the glass plate which remain still while the other parts are in a state of active vibration.

By varying the forms and dimensions of flat surfaces, whether of glass or any other material, as also the modes of vibrating them, a variety of beautiful results has been obtained. These experiments are very surprising to a person who witnesses them for the first time: the powder seems as if endowed with voluntary motion, and assumes these beautiful forms with a rapidity which the eye cannot follow. But the object of these inquiries is far higher than the gratification of curiosity: they throw considerable light upon the constitution of matter; the arrangement of its particles and the properties resulting therefrom, as elasticity, hardness, fragility, malleability, &c. A further discussion of the subject would lead us into a difficult department of science: we will therefore conclude this part of our subject with an easy and practical example.

When the points of support in a circular plane surface extend round the whole circumference, as in the parchment head of a drum, the whole plate or surface generally vibrates in one unbroken system; but the membrane may be struck or pressed in such a manner that an impulse communicated to one spot of the surface may not have time to extend itself over the whole surface before the retrogade motion of the disturbed point commences; in this case a nodal line will be formed at the limit of the sphere of the original impulse; thus, it has been found that in certain mining operations connected with military engineering, some sand has been strewed on the head of a drum, and the latter placed either over, or in near approximation to, a supposed excavation or subterranean gallery; any operations performed in the latter which are calculated to excite tremulous impulses in the air or the ground near it, will, when communicated to the drum, cause the dust or sand to assume certain forms, according to the nature of the impulse communicated to it, and engineers accustomed to those operations have been enabled to determine as to the nature of the operations going on beneath, and in what direction the locality was disturbed, by observing the forms into which the sand is thrown on the drum. In these cases, as in the former, the nodal lines are indicated by the form assumed by the sand on the vibrating surface.

In the cases which we have been considering, the surfaces are supposed to vibrate *transversely*, *i.e.*, in the direction of the thickness; but in some important experiments which have been instituted by Savart on the vibrations in a plane parallel to the surface, these he terms *tangential* vibrations, and they are most readily produced by *rubbing* the surfaces of bodies. His experiments were performed with square, circular, triangular, or longitudinal pieces of glass, with bars, with solid or hollow cylinders: these on being suspended lightly in the middle, and rubbed longitudinally with a wet cloth, will indicate nodal divisions of a complicated character; the nodes on the upper surface being vertically over the most actively vibrating points on the under surface and *vice versâ*. In a cylinder the nodal lines form a spiral, making four turns round it in its progress from end to end. On plane surfaces these nodes are detected by sprinkling dry lycopodium as before described; but with cylinders small rings of paper were hung upon it, and their state of agitation or rest indicated the presence or absence of vibrations.

3. *The Vibration of Curved Surfaces.*

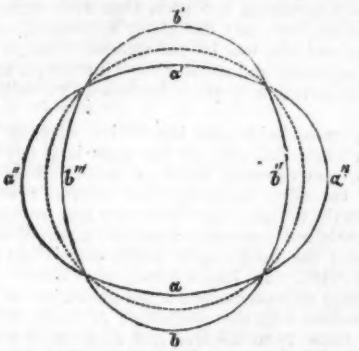
If we draw a violin bow across the edge of a glass goblet, or any similar vessel, a musical note is produced, which depends for its existence on several remarkable changes in the form of the glass itself; so minute indeed that the unassisted eye can detect no motion. It is, however, easy to prove that when the glass receives its first impulse from the bow it is thrown into the form *a a' a'' a'''* fig. 8, which the instant afterwards is changed to the position *b b' b'' b'''* the dotted circle being the position of the rim of the glass in a state of repose.

If we hang four little hooks upon the rim of the glass we shall find that they will be greatly agitated by the vibration of the glass, excepting at four points of its edge, at which points they will be at rest, or nearly so: these four points are equidistant from each other, and it will be seen that the point to which the bow is applied is equidistant between two of them: if the hooks be placed at those positions at first, they will remain there, but if at other points, they will travel round to the resting points.

The existence of these four points is very pleasingly shown by the use of lycopodium, the seed of the *Lycoperdon bovista*, which possesses a degree of fineness greatly exceeding the generality of powders, each grain being, according to Wollaston, less than the 85,000th of an inch in diameter,

For the use of this powder, a conical-shaped vessel is better than the shape of a goblet, but the latter will do.

Fig 8.



By sprinkling the lycopodium dust on the interior surface of the glass (to which a small quantity will adhere), and then vibrating the glass with a bow, a considerable portion of the powder will be shaken from off the surface, with the exception of four narrow lines of powder reaching from the top of the glass a considerable way down: in these lines there is very frequently not only the original portion of dust remaining, but an additional modicum derived from the other portions of the glass; and it will be always found that the point to which the bow is applied is midway between two of the lines.

To these modes of detecting the existence of vertical lines in the glass, having different properties from the remainder of the surface, we will now add another, which is, perhaps, more convenient in its application, and more appreciable; we mean, the presence of water, or any other liquid, in the glass. Water, coloured with litmus or ink to deaden the transparency, will answer very well.

If, when the glass is about half filled with water, it be vibrated by passing the moist finger round its edge, the liquid surface becomes broken up into a figure of four fans, which rotate in the direction and with the velocity of the finger, the latter being always midway between two of the fans, its pressure causing the point on which it rests at any given instant to assume the condition of a node; but if the glass be excited to vibration by means of a bow, the surface of the water is thrown into the form represented by fig. 9. From four equidistant points of the glass emanate four fans of liquid undulations, which proceed nearly to the centre of the liquid surface; and it is seen that, whatever part of the glass be chosen as the point of excitation, one of the fans emanates from beneath that point. The oblique action of two contiguous fans raises a faint ridge which proceeds from each node to the centre; while the extreme ends of the four fans form, in meeting at the centre, a net-like figure, which is generally that of an imperfect square.

Fig. 9.

The last corroborative evidence of the existence of these four remarkable points in the circle of the glass which we shall mention, is obtained by the use of any oily or viscid fluid, such as is calculated to adhere to glass more than water does. If the vessel be half filled with such a liquid, (care being taken to preserve the inner surface of the glass, between the oil and the rim quite dry,) and vibrated by one rather decided stroke of the bow, it will be seen, on viewing the glass horizontally, that four vertical curves are formed by an upward starting or motion of the oil in four places, by which a small stratum is left adhering to the surface of the glass, and, in analogy with previous instances, the point of excitation occupies a position immediately over the highest point of one of these curves.

There are many other methods of proving the existence of four equidistant and quiescent points round the surface of the glass; but these instances will suffice. Let us now attend to the explanation of the phenomena. As in the stretched cord, so in the goblet; the action of the bow throws the vibrating body into a new curve, which, in the present case, is an ellipse.

When the impulse has produced the greatest displacement of which it is susceptible, a momentary state of rest occurs, in which the glass is elliptical; but its elasticity will not permit a continuance in that form: the depressed portions acquire an outward tendency, and the elongated portions a tendency towards the centre; there must therefore be points where these opposite tendencies neutralize each other, and those points must necessarily be the parts of the glass which were not originally disturbed from their position of repose.

By the time the segments have regained their original position, they acquire a momentum which carries them beyond the circle of repose, the two outer segments passing within, and the two inner segments passing without. A moment's consideration will show that this action must generate an ellipse, of which the longer axis is at right angles to the longer axis of the former ellipse *a a a a* which it has just superseded: this we may represent by the ellipse *b b b b*, fig. 8.

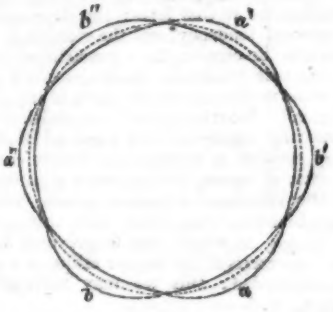
It will now be well understood that the same causes which produced the destruction of the first ellipse will act with equal force on the second; elasticity will carry the displaced segments back to their original positions, and in so doing will generate a momentum sufficient to carry them beyond that boundary, and thus give rise to the formation of an ellipse similar to the first, and at right angles to the second. Thus these reciprocations succeed each other until the resistance of the air and other circumstances finally, but gradually, subdue them; for it should be understood that each successive ellipse is less elongated than the preceding.

The description of these changes necessarily takes a considerable time, but the changes themselves occur with almost inconceivable rapidity, being several hundred times in a second; and as our visual powers are quite inadequate to detect the individual members of such a rapidly-recurring series, whatever effect either ellipse considered separately is calculated to produce, we estimate the result as if both ellipses were co-existent; and this will now enable us to explain the quadripartite phenomena before described. If water be contained in the glass, the transformation of the latter from a circular to an oval form necessarily occasions a flow of water from the flatter towards the smaller ends of the ellipse: when the latter is reversed, a flow occurs in the opposite direction, and as the eye cannot detect any interval of rest between the two, an impression of their simultaneous existence is left upon the mind. Thus the form of fig. 9 is presented to us, and thus shall we be enabled to apply the same mode of reasoning to the points of rest indicated by the hooks, powder, &c. While the four segments of the glass are rapidly vibrating to and fro, the four intermediate points, being urged as it were, between two equal forces, do not move at all, and any bodies placed against those points will be nearly as quiescent as if the glass were not vibrating: thus if the little hooks be symmetrically placed equidistant from each other, and the bow be applied midway between two of them, the two resulting ellipses will cut each other at the points on which the hooks are placed, and then those points become nodes or quiescent points which are not likely to disturb the hooks placed upon them; but if the latter be placed at other points, or if the bow be applied other than midway between two of them, the hooks partake of the vibratory action of the parts of the edge on which they are resting, and are gradually shaken to those points where the agitation is less vigorous, and finally attain the nodal points.

With respect to the lycopodium dust, it is evidently shaken from those parts which are actively vibrating, because its adhesion to the glass is very slight; but as there is no motion occurring at the nodes, there is no reason why it should be removed from thence, and we consequently find that a line of powder remains on the quiescent points. It must here be remarked that although, for convenience, we have spoken of the glass as a vibrating circle, the effect is obviously carried a considerable distance towards the bottom, and instead of nodal *points*, we have nodal *lines*, down which the powder remains undisturbed. Thus may these interesting phenomena be analyzed, and the rationale of their production traced step by step; but the inquiry by no means stops here: we have treated of that combination of circumstances which will induce a system of four vibrating segments in the glass, but we shall find that the same principle, modified in its individual application, is discernible under other conditions, into the consideration of which we will now enter

If the impulse given by the bow be less energetic than that which produced the effects before described, there exist good reasons for believing that the glass assumes a form

Fig. 10.



analogous to $a\ a\ a$, fig. 10. Let us suppose that the bow is applied at the point of the glass marked a: a segment is drawn out of the circle, as before, but by the time the impulse reaches the nodal points on either side of it, the elastic tension urges the two adjacent portions, $b\ b$, within the circle, to restore equilibrium: these three segments together take up a semicircumference, which acts upon the opposite semicircumference by momentum, thus:—the two lateral segments, $b\ b$, by passing too far towards the centre, induce a protuberance in the more remote portions, $a'\ a''$, which, in their turn, generate a third depression at b''; thus, then, we obtain three segments exterior and three interior to the original circle of repose, which give to the periphery, taken as a whole, the form indicated by $a\ a'\ a''$. Let us now bear in mind the manner in which one ellipse gave rise to another ellipse which immediately succeeded it, and we shall have but little difficulty in concluding that the same principles will convert the heart-shaped figure, $a\ a'\ a''$, into a similar figure, $b\ b'\ b''$, the elongations of the former coincide radially with the depressions of the latter, and the depressions of the former with the elevations of the latter. There will be obviously in this case six points where the two superposed figures cut each other, and these points, from the principle before alluded to, will be at rest.

This, it will be observed, is a theoretical deduction of what would occur if the primitive impulse were not energetic enough to draw a quarter of the circle out of the position of repose; but we will now proceed to give practical illustration of the existence of these three-sided figures. In drawing the bow across the edge of the glass, it will be found that more than one sound can be heard; frequently four or five; all musical and rich, but all different in pitch. If now, by the presence of water in the glass, we obtain a figure of four undulatory fans on the surface, we shall invariably find that the musical note elicited at that moment is the lowest in point of pitch of all those which it is capable of producing; and as the surface is never broken up into a less number than four vibrating segments, and four nodes between them, it will be convenient to call the musical note produced at that moment, or by that mode of vibration, the *fundamental note*. If now we draw the bow smartly across the edge of the glass, with a motion which may be called quick rather than forcible, we shall obtain the next higher tone, and at that moment the liquid surface presents six vibrating fans of undulæ, equidistant from each other, and separated by six points, where comparative quiescence is observed.

By this experiment, and by the hooks, lycopodium, &c., it is seen that the six-sided figure is due to two superposed three-sided figures.

With a slight modification of the mode of handling the bow, which it is difficult to describe, we can next produce a tone higher in pitch than that which accompanied the six-sided figure; and the invariable result will be a figure of eight sides, that is, eight liquid fans of undulæ will emanate from the sides of the vessel towards the centre of the liquid, and be separated from each other by nodal lines as before. The reader will not require that we should retrace our steps in detailing the production of this eight-sided figure, for it will be readily understood. It must be remembered that, when we say this note is invariably accompanied by a figure of eight sides, we mean that the note is the next higher in pitch to that which produced the six-sided figure; and in further evidence of the same fact, in will be found that the fourth tone which the glass is susceptible of producing will always be accompanied by a figure of ten sides, whether the indicator employed be water, lycopodium, or wire.

Generally speaking, not more than four different tones can be elicited from any one glass; sometimes, however, a fifth is appreciable, but be the number what it may, the vibrating segments and nodes always increase in number by twos as the elevation of pitch increases, they being 2, 4, 6, 8, &c.

A very remarkable and instructive effect is, however, produced, when the edge of the glass is at any one point prevented from vibrating freely: a violin performer is well aware of the effect resulting from placing a sourdine, or damper, on the bridge of his violin—the tone acquires a peculiar and subdued character, from the circumstance of the vibrations of the bridge upon which the strings rest being interfered with. In like manner, any small instrument which would act as a damper when placed on the edge of a glass, interferes with the production of those effects which naturally result from the free and unshackled vibration of the glass. We have employed a small steel instrument which clasps the edge by means of a screw, but other modes may be devised, provided that the damper where it clamps the glass presents a certain amount of plane surface probably not less than a tenth of an inch. When an impediment to free vibration, such as this, is employed, that force of vibration which would otherwise produce a four-sided figure, or one composed of two superposed ellipses, will produce but three vibrating segments, one of which is diametrically opposite the damper, and the other two so situated as to form with the third nearly an equilateral triangle, *provided* the bow be applied immediately opposite to the damper; but if it be applied at about 45° on either side of that point, four segments will be formed just the same as if no damper were placed on the edge. These effects may be tested by employing water in the glass. If we, in similar manner, produce all the other tones of which the glass is susceptible, retaining at the same time the damper on the edge, and applying the bow immediately opposite to it, we shall find that the number of ripply fans on the surface of the water is one less than if no damper were present, the numbers being respectively 3, 5, 7, 9, &c. It is not now necessary to trace in detail the causes of this; precisely the same mode of reasoning as that just adopted will avail for all, the difference of number being dependent on the difference of energy in the first impulse, or, which amounts to the same thing, the extent of curve included in the first segment.

All the phenomena which we have been detailing are produced by the violin-bow; but if the moistened finger be employed, we perceive four fans of undulæ revolving in the direction, and with the velocity, of the finger: the reason of this revolution is, that, as fast as a vibrating segment is produced by the friction of the finger, it is interfered with by another formed by the finger at the succeeding moment a slight distance from it; and thus new segments are continually forming, which give a rotatory appearance to the surface of the liquid.

4. *The Vibration of a Confined Column of Air.*

If we blow through a hollow tube, open at both ends, no sound is produced; we merely cause a wind to circulate through the tube which is communicated to the external air. Every particle of air in the tube is moved in the same direction, and that is precisely what we mean by the term wind; but when the lips are nearly closed, as in playing the flute, and the air is introduced in a very fine and narrow stream or current, that stream acts with different momentum on different parts of the aërial column: the first effect is a motion of particles from the mouth-hole towards the other extremity of the tube: this is retarded by the inertia of the more advanced particles: the resistance occasions a slight pressure of particle upon particle: this pressure is directly opposed by the elasticity existing between the particles, which elasticity beyond a certain point, overcomes the impulse derived from the mouth, and the advanced particles are driven back again to their original position, and even beyond it, in accordance with the universal law of momentum: this retrograde movement engenders a slight compression of particle upon particle in the opposite direction, and a new impulse, from the mouth-end to the remote end is the consequence; and thus a longitudinal vibration of the column of air takes place.

It must be borne in mind that the motion of particles of which we are speaking, does not embrace a sensible amount of distance, but is confined within very minute limits. In the case of wind the particles of air move though a sensible distance, and change their places; but in these instances of longitudinal vibration, the positive amount of displacement which each particle suffers is exceedingly small, and is always recovered again by the retrograde movement.

In such instruments as the clarionet, the tube full of air is exempted from such an impulse as would generate a wind, by the intervention of a piece of apparatus at the end to which the mouth is applied. This consists of a reed or small elastic slip—fixed at one extremity, while the other is free to move, but comes into contact with the opposite side of the orifice: this contact, which is easily disturbed, is broken by the force of the air from the mouth; but this is only for a minute portion of time; the elasticity again urges it to its former position of contact with the opposite side: this portion of time, however, during which contact is broken, small as it is, is yet sufficient to allow a certain portion of wind to pass through the opening, and thus produces a sudden condensation of air in the tube: the momentary closing, however, of the aperture, allows that condensed portion again to recover its wonted tension: but the following opening of the aperture, and consequent emission of another modicum of breadth, again induces a condensation; and these reciprocations occur as often as the contact between the elastic reed and the opposite surface is broken and renewed again.

The organ-pipe is another instance of the vibration of a column of air; but these admit of two modifications—the diapason and the reed-pipes: the former resembles the flute in so far as this, that the sound resulting from the vibration of the air contained therein, is wholly dependent on the length of the pipe itself, and the position of an orifice at which the air can escape: but in the reed-pipe there is an analogy to the principle of the clarionet; the air contained therein, besides the vibration in its own length, has the second effect of setting in motion one or two vibrating tongues or reeds at one end of the tube: these tongues admit of being lengthened or shortened so as to adjust the rapidity of the vibration of the whole column of air in the tube, and the latter depends, as will be shown hereafter, on the length of the tube.

Such instruments as the trumpet, horn, bugle, serpent, &c., depend for the production of their respective sounds partly on the length, and form of the tube through which the air is thrown into agitation, and partly on a peculiar management of the lips of the performer, by which he regulates the quantity and velocity of the air which is impelled into the instrument.

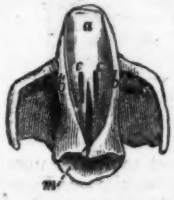
In the flageolet, as in the flute, and some other instruments, there is no vibrating tongue or reed, but the whole sound is due to aërial vibration: it is necessary however to bear in mind that in wind instruments of every description, the important and fundamental source of sound is the longitudinal vibration of a column of air contained within the tube: the manner in which these vibrating columns of air are bisected, and sometimes trisected, in their whole length cannot at present engage our attention.

5. *The Voice.*

The most important of all the sources of sound is the voice, that faculty which enables us best to express our feelings, affections, and sentiments; "which, modified by the organs of speech, gives utterance to the hidden things of the heart, and alike enables the sage to communicate his wisdom and the fool to babble his folly. And here we have already made a distinction that will require to be attended to: the voice is one thing; it is common to us with beasts, whose cries will express pleasure or pain, rage or fondness; speech is another thing, and is the peculiar prerogative of man. It is true some animals, such as the jay, the parrot, &c., can articulate, but this is not to speak: speech is the expression of thought, and 'monkeys don't speak,' says Lordat, 'because they have nothing to say.' This simple observation, which is as philosophical as it is terse, might have saved a world of trouble to different anatomists, who spent much time in finding out, by peculiarities of structure in the organs of voice, why no animals spoke but man. Now anatomy is totally unable to resolve the question, inasmuch as several animals, who do not speak, can nevertheless articulate when taught to do so by man; it is evident, therefore, that their natural dumbness is not to be attributed to any organic cause."

The vocal mechanism in man may be considered as consisting of *lungs* or *bellows*, capable of transmitting by means of the connecting *windpipe*, a current of air through an apparatus contained in the upper part of the windpipe called the *larynx*, in which are placed two cords whose vibrations supply sounds to the variable cavity, consisting of the pharynx, mouth, and nose, and these organs convert the sounds thus furnished to them into speech. Thus the organs of speech are not very complicated, being chiefly the lips, teeth, tongue, and palate, all receiving their supplies of sound from behind, and fabricating those sounds into words. A more accurate idea of the situation of these vibrating cords, commonly called *chordæ vocales*, may be had in fig. 11, in which they are represented as they would be seen by a person looking down the windpipe from above, and able to notice the situation in the aperture. In this figure

Fig. 11.

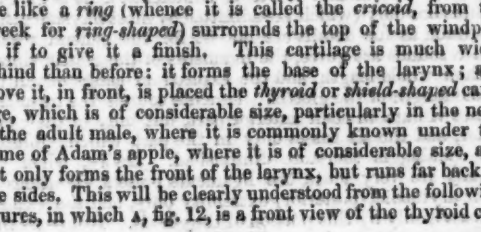


a is the *epiglottis* situated in front of the opening, and ready to shut it down so as to prevent the entrance of any substance foreign to it: two ligaments *b b* proceed from it: these are prolonged backwards so as to constitute as it were a sort of superior dilated orifice of the windpipe. The true opening of this is seen deeper down, at *m*, and to this opening is given the name of *glottis;* while at either side of it are stretched *c c*, the *chordæ vocales*, or vibrating cords, on which the production of the voice depends; and above these are seen two little depressions or cavities termed *ventricles of the larynx*, the object of which appears to be to leave space for the vibrating of the cords.

The voice is known to be formed at the exact point termed the glottis by the following experiments:—If an incision be made into any part of the windpipe below the glottis the voice is immediately lost, but if the aperture be stopped up by closing it with the hand, by placing a roll of lint in it, &c., the voice is restored. If, on the contrary, the incision is made above the *glottis*, the voice is in no way affected. In the one case the air necessary to the production of sound escapes below the glottis, and no voice is produced; while in the other case the air escapes immediately after passing through the glottis, and the voice is perfect. Other experiments, which we cannot here detail, have also proved that it is by the vibration of the chordæ vocales of the glottis that the sound of the voice is accomplished.

But this is not enough to produce sounds of sufficient loudness for the general purposes of life, nor can we see by its means how sounds are varied in character and pitch. The office of the larynx shows how these important requisites are effected. The larynx is placed like a box or case round the upper part of the windpipe, to afford a firm and to some extent a resonant fabric for the attachment of the parts immediately concerned in the production of voice. The larynx is composed of these principal cartilages; the one like a *ring* (whence it is called the *cricoid*, from the Greek for *ring-shaped*) surrounds the top of the windpipe as if to give it a finish. This cartilage is much wider behind than before: it forms the base of the larynx; and above it, in front, is placed the *thyroid* or *shield-shaped* cartilage, which is of considerable size, particularly in the neck of the adult male, where it is commonly known under the name of Adam's apple, where it is of considerable size, and not only forms the front of the larynx, but runs far back on the sides. This will be clearly understood from the following figures, in which A, fig. 12, is a front view of the thyroid car-

Fig. 12.



tilage, separated from all the rest; B a side view of the same, in which *a* is the anterior, and *p* the posterior extremity: C is the cricoid or ring-shaped cartilage, with its deep part

behind, while the thyroid fits down upon the narrow part in front in a way we shall presently describe. The third cartilage is the *arytenoid*, or funnel-shaped cartilage, which may rather be described as two distinct cartilages, one for each side, placed on the top of the elevated part of the cricoid cartilage; and thus completing the back part of the larynx, which, when all its parts are put together, presents the appearance represented in fig. 13, when viewed in front; fig. 14, when viewed from the side; and in fig. 15, when viewed from behind: and in each of these figures *a* is the thyroid cartilage; *b* the anterior or narrow, and *c* the posterior or broad part of the cricoid cartilage; *d d* the arytenoid cartilages, resting on the latter and meeting at the summits: *e e* the horns of the thyroid cartilage, and *f* the epiglottis.

Fig. 13.

Fig. 14.

Fig. 15.

These several cartilages are not fixed, but moveable upon one another by muscles; the chordæ vocales, also, are by no means to be considered as simply elastic ligaments, strained between their extreme points, and obliged to vibrate when blown with sufficient force: they are living ligaments, endowed not with a mechanical but with a vital elasticity, and supplied with muscles, which regulate all their motions to the nicest degree, placing them in that state of tension and parallelism which is necessary to the production of sound, and not only that, but moving them in every the slightest change of tone, so that we cannot doubt that every turn or trill on the human voice is produced by a succession of muscular contractions, as surely, though not so obviously, as a shake on the violin, under the fingers of a skilful player. Thus the larynx is a living musical instrument, capable of giving or withholding its sound, so long as no part of its vital apparatus is impaired, and whose vibrations depend not upon any external impressing agent, but upon a power existing within itself.

Many theories have been formed as to the manner in which the chordæ vocales act in the production of the different tones of which the human voice is capable. Some supposed that the greater or less tension of those cords produced the acuter or graver sounds. Others thought that the tones varied according as the glottis was more or less open: others, that the raising or depressing the larynx, which any person may observe by placing his hand on his own throat as he sings the gamut, afforded the true explanation. M. Magendie, however, has set the matter at rest by direct experiment: it will be sufficient for us to give his conclusions only (which are admitted by most physiologists), inasmuch as his details are not fit for the general reader. When sounds are grave, the ligaments of the glottis vibrate in their whole length, and the expired air passes out in the whole length of the glottis. In acute sounds, the ligaments do not vibrate in their anterior part, but only in their posterior, and the air passes only in the part which vibrates; the opening is therefore diminished. Lastly, when the sounds are very acute, the ligaments present vibrations at their arytenoid (posterior) extremity only, and the expired air passes only by this portion of the glottis. It appears that the extreme limit of acuteness in sounds happens when the glottis closes entirely, and air can no longer pass through the larynx.

These conclusions are supported by a well-known occurrence, and that is, the prominence of the thyroid cartilage (Adam's apple) in the neck of men, and not in those of women and boys. The explanation is this: the chordæ vocales are attached behind to the arytenoid, and before to the thyroid cartilages; consequently if these cartilages remove to a greater distance from each other, the cords must become longer. But this removal cannot take place by the retiring back of the arytenoid, for it is placed just against the gullet, and if it went further back, would interfere with our swallowing: it must therefore be accomplished by moving forward the thyroid, and this takes place in boys just at the age of puberty, when the voice becomes of a deeper tone, in consequence of the lengthening of the cords, and is said to be *cracked;* the individual produces sometimes a high tone, sometimes a low one, not having yet learned exactly to adapt the muscular contractions to the new state of his vocal chords. This change never takes place in women, consequently their voice at all times retains the high tone it had in childhood.

It will now be understood how a variety of tones may be produced by means of the apparatus described; but how these tones are uttered with a stronger or weaker accent is not so clear. It is probable that the greater or less quantity of air forced out in a given time is the chief means of increasing or diminishing loudness, by increasing or diminishing the *extent* of the vibrations. A certain adaptation of the parts, however, is here required, otherwise not only would the intensity be increased, but the tone elevated in pitch. When the wind is blowing moderately through a key-hole a low murmuring sound is produced; but when the strength of the wind is greatly increased by a storm the low murmur becomes a shrill whistle. The same effect would take place if our glottis were immoveable every time we attempted to shout or call loudly; that it does not take place, is the result of our larynx being a vital instrument placed under the governing influence of the mind, or acting in unison with it, and therefore not imitable, except to a certain limited extent, by any of those mechanical contrivances which, under the name of speaking figures, have from time to time excited the curiosity of the public.

The quality of voice, the timbre, or that peculiar property which enables us to distinguish one individual among a thousand, and informs us of so many of the actions of matter, both animate and inanimate, is difficult of explanation. This quality of sounds is the name given to the difference of notes of the same pitch when produced by different means. A flute and a violin may be in unison, but the notes are still quite different sounds, and although each may be due to the same number of vibrations, yet one of them cannot be mistaken for the other. It is this kind of difference which distinguishes the voice of one man from that of another, and serving as it does, to connect the voice with the particular person, it seems an almost indispensible property of sounds, in order that language may be a medium of intercourse between man and man.

We can give no explanation of the *quality* of sounds: we may indeed surmise that the proportions and nature of the sounding body are important elements: the weak and wailing voice of infancy may result from the soft, spongy, and yielding state of the cartilages; the more powerful and resonant voice of manhood may be the effect of the parts having acquired their due proportions, hardness, and strength: alterations produced in the voice by disease may be due to the lining membrane of the larynx becoming thickened and enlarged by inflammation; and, finally, the disagreeable, broken, and cut voice which sometimes accompanies old age may be referred to an impeded freedom of motion, a want of uniform density, on account of the deposit of bony matter in different parts of the cartilages. All these causes may have their influence, and further modications may be accounted for by varieties in the thickness, consistency, length, and structure of the chordæ vocales: the nature and form of the cavity through which the voice passes after being formed, must also be taken into account.

It does not fall within our present object to enter into details respecting speech and articulation; nor, at present at least, to trace the curious variations in the organs of voice among the lower animals.

In another Supplement we shall have to notice the voice as a musical instrument, the construction of which we have thus far endeavoured to explain.

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